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Optimization classification, algorithms and tools for renewable energy: A review

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ABSTRACT

Renewable energy technologies' systems are major components of the strategy to reduce harmful emissions and deal with depleting energy resources. It is necessary to deploy renewable energy sources in the best possible way such that cost is minimized and generation is maximized. In this paper, we present a review of different optimization methods for deployment and operation of renewable energy sources based generating units. Unlike other existing reviews, we carry out a general review of this research area, without limiting ourselves to any particular issue or geographic location. We examine this area with respect to different types of renewable energy sources, different modes of operations, types of objective functions for optimization and different geographical areas from which research publication are emanating. We present a general resource allocation problem and specify different possibilities for input, output, objective function and constraints. In addition, we review different objectives used in defining the optimization problems. We also present different types of linear and non-linear optimization algorithms used in renewable energy sources. Finally, we review optimization techniques for applications with respect to different end users.

Contents

1. Introduction

Emerging socio-economic considerations of the world challenges scientists and researchers to deal with increasing demand of the electricity to reduce harmful emissions. The world energy

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demand will increase by 56% from 2010 to 2040 [1], which in turn is expected to increase carbon dioxide emissions from 31.2 billion metric tons in 2010 to 45.5 billion metric tons in 2040. Furthermore, fossil-based oil, coal and gas reserves will deplete rapidly in the next decades [2]. These prevailing and forecasted circumstances are compelling the scientists to adopt two prong strategy, which consists of developing energy efficient systems [3,4] and replacing fossil fuel based power generating units with those using renewable energy sources.

The renewable energy sources are being used for many applications. e.g., heating [5] and generation of electricity [6] with minimum carbon dioxide emissions [1]. Both grid connected and stand alone renewable energy sources systems are available in the market [7]. The former system is normally suitable to fulfill the high energy needs while the latter is useful for remote residential users. The energy generating units based on renewable energy sources are less reliable as compared to the conventional fossil fuel-based power generating systems due to their intermittent nature. Integration of different renewable energy sources coupled with energy storage system can add reliability in the power systems [8]. This integration is termed as hybrid renewable energy sources.

Different renewable energy sources have different electricity generation capacity. It is important for the government and utility companies to know the exact capacity of different renewable energy sources at different locations to develop and deploy the power grid efficiently. Appropriate deployment of renewable energy sources will ultimately reduce the operation and maintenance cost of the energy generating units [9]. Cost reduction and power generation maximization are two main objectives when planning for the deployment of renewable energy sources. Different optimization techniques have been proposed to achieve these two objectives. Various optimization models are available in the literature, namely, renewable energy models, emission reduction models, energy planing models, energy supply and demand models, forecasting models and control models [10] for efficient utilization of the renewable energy sources.

A comprehensive review of the optimization methods applied to renewable energy sources is available in [7], but there are increasing number of new optimization methods being proposed in the field of renewable energy sources. Therefore, this paper depicts an updated review of the optimization methods being used to solve different problems relating to deployment and operation of renewable energy sources based electricity generating units. After a thorough search[1] and scrutinization, only those articles which focus on mathematical optimization models to solve different problems related to renewable energy sources are included in this review.

Initially, we show the increasing interest of research community in optimization techniques for renewable energy sources. We categorize this interest into four different areas of research.

(1) Research focused with respect to renewable energy sources.
(2) Research focused with respect to configuration/mode of operation.

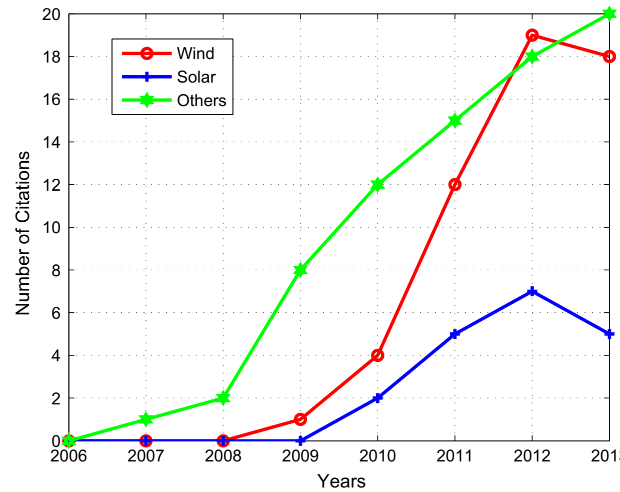

Fig. 1. Year-wise citations for different renewable energy sources.

(3) Research focused with respect to objective function.
(4) Research focused with respect to geographical area.

1.1. Year-wise distribution of articles focussed on different renewable energy sources

Hydro power generation is mature and considered as a first option for generating electricity. Hydro power is one of the major subjects of optimization method development in the area of renewable energy sources. Due to inadequacy of hydro power generation, researchers started focusing on harness wind and solar potentials. Fig. 1 shows the increasing interest in the area. It depicts that the research community predominantly focuses on the solution of different problems related to the wind energy by using different optimization techniques. Solar energy systems are the second single largest renewable energy sources which are being investigated for finding optimal solutions using different optimization techniques. There are significant number of papers in this review which are focused on other miscellaneous renewable sources such as hydro, geothermal, biomass and biofuel.

1.2. Year-wise distribution of articles focused on Grid connected vs Stand-alone operation

Renewable energy sources can be used in grid connected as well as in stand alone modes. Grid connected hybrid renewable energy sources are promising areas of research [11] as these are expected to provide the same level of power supply reliability that can be achieved from the conventional fossil fuel based energy systems [12]. Fig. 2 shows the breakdown of the articles included in this review with respect to their emphasis on grid connected approach and the stand alone mode of operation. The bulk of the research work is targeted towards the grid connected mode of operation. The solution to the intermittent nature of renewable energy sources is being sought into the hybrid grid connected renewable energy sources [11].

1.3. Year-wise distribution of articles focused on different optimization functions

Articles included in this review have used different optimization techniques for solving problems relating to renewable energy. The problems can be broadly categorized as planning optimization, production optimization, operation optimization and emission optimization. Fig. 3 shows the contribution of different

[1] An initial search related to the optimization methods applied to renewable energy sources was conducted using Google Scholar with search terms including “renewable”, “sustainable”, “energy”, “optimization” and “optimisation”. The archives of journals and conferences were searched to find the relevant material. The material found was further scrutinized for relevance. General criteria on the basis of which different articles have been included in this review are as follows.

- Articles discussing all areas relating to renewable energy planing, design, deployment and operation.
- Research articles which have discussed different mathematical optimization models and techniques applied to renewable energy sources.
- Research articles since 2006.

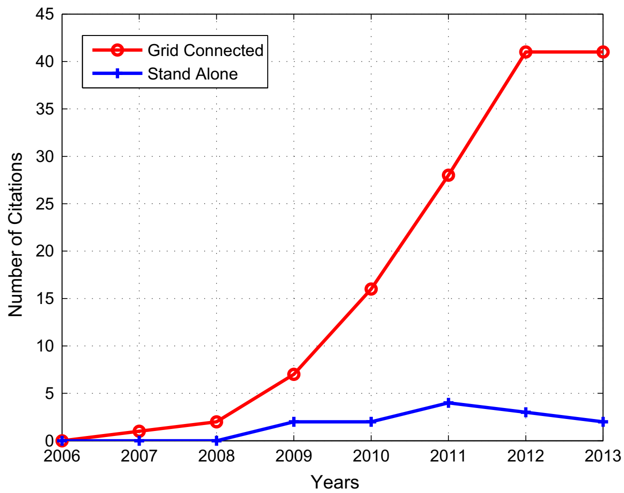

Fig. 2. Grid connected vs stand alone.

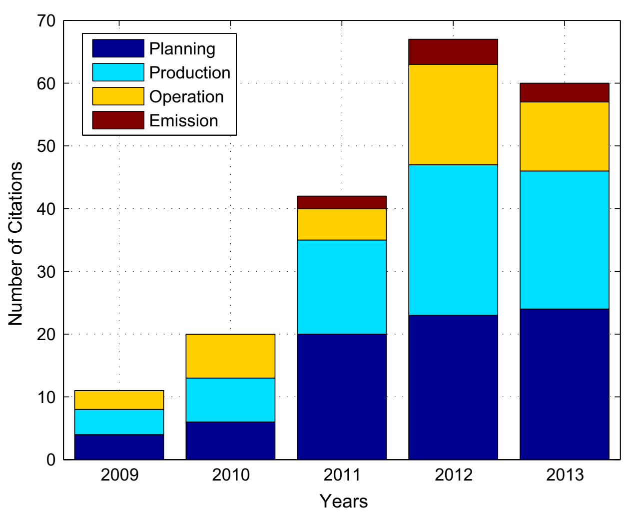

Fig. 3. Year-wise citations w.r.t objective function.

articles focused on each problem over the past few years. It is evident from the statistics that bulk of the initial optimization work is focused on planning, production and operation. With increasing use of biofuels as renewable energy sources and world's focus to reduce carbon dioxide emissions [13–15], the interest of research community is also increasing towards finding the optimal energy systems in order to minimize the harmful emission.

1.4. Continent wise distribution of articles

In Fig. 4, the articles included in this review have been classified with respect to the affiliation of authors to specific country or continent. As far as the number of research articles are concerned, the ongoing research is being led by Asia with 50% publications. Within Asia, China and India are leading this surge due to obvious reasons: both countries are developing and need to sustain their growth by finding alternate and sustainable energy resources [16,17]. Furthermore, China is contributing almost 50% of the world carbon dioxide emissions [18] and is struggling to reduce it. The continent with the second most research publication is Europe with 26% publications, followed by North America and Africa with 14% and 9% of the total publications, respectively, whereas rest of the regions are only contributing 1%.

This review paper is organized as follows: Section 2 presents a brief overview of the topic and comparison between the salient

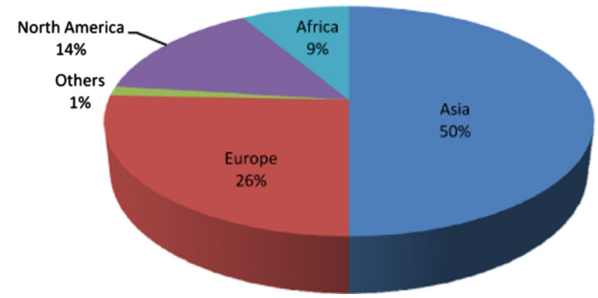

Fig. 4. Distribution of citations w.r.t. to affiliation of authors to different continents.

Table 1
Existing reviews/surveys relating to optimization in renewable energy. W=wind, S=solar, B=biomass, EA=evolutionary algorithm, CS=country specific review, App=application.

Ref. no.	Review type				Optimization type		Renewable energy type				EA
	Algo.	CS	App	Generic	w.r.t. structure	w.r.t. obj.	W	S	B	Other	
[7]	√		√			√	√	√	√	√	
[21]	√		√		√						
[23]			√				√				
[24]			√			√	√	√		√	
[25]			√					√		√	
[26]	√							√			√
[27]			√					√			√
[28]			√						√		
[77]	√		√				√	√		√	√

features of this review and the other reviews on the topic. Generic resource allocation problem is reviewed in Section 3. Section 4 reviews conflicting objectives in renewable energy sources. Section 5 describes different optimization types used and Section 6 reviews optimization techniques applied to renewable energy sources planned for different end users.

2. Optimization related surveys/reviews

A summary of previous surveys/reviews on the topic is shown in Table 1. It can be inferred that there is no comprehensive survey available that covers all the renewable energy sources. The most recent survey [7] that illustrates evolutionary algorithm (EA) based renewable energy sources was published in 2011. The main focus of the authors is EA for single- and multi-objective optimization of renewable energy sources. Most of the reviews available in the literature are either renewable energy sources specific or algorithm specific. Furthermore, these reviews are mostly country specific. In [19], the authors focused the layout problem of wind farms with the objective of minimizing overall cost. They are of the view that iterative non-deterministic algorithms such as genetic algorithms, differential evolution, particle swarm optimization, and simulated annealing are some of the most suitable approaches to address the problem of generating efficient, rather optimal, layouts of wind farms. In [20], the authors have used multi-objective optimization methods by employing evolutionary algorithms to solve the problem of placement, sizing, design, planning and control in the field of stand-alone hybrid renewable and sustainable energy. In [21], the authors have reviewed some of the most popularly distributed renewable generation placement methods, including 2/3 rule [22], analytical methods, optimal power flow, mixed integer non-linear programming, various types

of artificial intelligence optimization techniques and hybrid intelligent systems. This study was aimed at reviewing the optimal placement of distributed renewable resources satisfying various economical, social and technical constraints. Ref. [7] is the most comprehensive review on the topic so far covering most well-known renewable energy resources. This paper provides an overview of the latest research developments concerning the use of optimization algorithms for design, planning and control problems in the field of renewable and sustainable energy. In another review [23], the authors have reviewed various optimization techniques using genetic algorithm for optimal micrositing of the wind turbines with the objective of minimizing cost per unit power. A review has been presented in [77] regarding hybrid renewable energy sources to optimally size the hybrid system components to meet all the load requirements with possible minimum investment and operating costs. In [24], the authors have reviewed the simulation and optimization techniques, as well as existing tools that are needed to simulate and design stand-alone hybrid systems for the generation of electricity. This review article focused on optimization problem with the objective of minimizing net present cost[2] and levelized cost[3] of energy. In [25], the authors have presented a detailed overview of hybrid renewable energy systems with emphasis on solar photo-voltaic based stand-alone applications. Various important parameters of such systems, such as unit sizing and optimization, modeling of system components and optimal energy flow management strategies, are specifically reviewed. In [26], the authors have reviewed various stochastic optimization techniques implemented in solar energy systems to reduce system total cost, increased life cycle savings and thermal efficiency. In another review article [27] regarding solar energy systems, the authors provide the updated status of research and applications of various methods for determining solar panel tilt angle using different non-linear optimization techniques, namely genetic algorithm, simulated annealing, particle swarm optimization and artificial neural networks. In [28], the authors have reviewed different deterministic and stochastic mathematical models to optimize the forest biomass supply chains for electricity generation.

This article reviews the recent work published on optimization techniques applied to different renewable energy sources for different objective functions. The existing literature in this area is classified with respect to different renewable energy sources, different modes of operation and different types of objective functions for optimization. We summarized different objectives used to define optimization problem, i.e., maximization of revenue, minimization of emission, maximization of reliability, maximization of production, minimization of operating cost, minimization of fuel cost, maximization of life span and minimization of waste material. We analyze the relationship between different objective functions and present a summary of latest tools and models. These tools are used to evaluate a particular renewable energy sources at some specific location with respect to its financial and technical feasibility. This review article provides an insight to the readers regarding recent developments in the area and serves as a foundation for further research. In addition, it can be used to decide optimal mix of renewable energy sources for particular geographical area to meet the energy demands of that specific area.

[2] The difference between the present value of cash inflow and the present value of cash outflow.

[3] Total cost (installation, maintenance and operational) divided by the total energy produced during the life span of the project.

Table 2
Generic resource allocation problem (inputs, outputs, objectives, constraints).

Given/inputs:	(any combination)
	Number and type of renewable energy sources units
	Amount of land used
	Atmospheric conditions
	Technology of renewable energy sources units
	Mode of operation
	Operational life
	Efficiency
	Operation and maintenance cost
	Meteorological conditions
	Geographic locations of renewable energy sources units
	Renewable energy sources related custom inputs
Find :	(any combination)
	Total generated energy
	Number and capacity of generating units
	Total investment
	Life time of the renewable energy sources
	Operation and maintenance cost
	Reliability of renewable energy sources
	Expected profit
	Estimated land use
	Best mix of renewable energy sources units
	Best renewable energy sources deployment/placement
	Renewable energy sources related custom variables
Objectives :	(any combination)
Minimize:	*Total cost of the system*
Minimize:	*Cost per unit of energy produced*
Minimize:	*Land area*
Minimize:	*Investment*
Minimize:	*Total maintenance cost*
Minimize:	*Noise and pollution emission*
Minimize:	*Loss of power supply probability*
Maximize:	*Thermal efficiency*
Maximize:	*Total power generation*
Maximize:	*Reliability of the system*
Maximize:	*Profit*
Maximize:	*Life span*
Maximize:	*Total revenue*
Maximize:	*Renewable energy sources related custom objectives*
Constraints:	(any combination)
	Environmental/atmospheric constraint
	Demand/load management constraint
	Economic/budget constraint
	Storage capacity of the batteries
	Charge and discharge rate constraint
	Carbon dioxide emission constraint
	Social/regulatory constraint
	Loss of power supply probability constraint
	Life time of components constraints
	Power rating of renewable energy sources units constraints
	Maximum power flow limits of distribution lines
	Area of the land to be used for renewable energy sources
	Generating units
	Cost of energy constraints
	Renewable energy sources related custom constraints

3. Generic resource allocation problem in renewable energy sources

The generic resource allocation problem consists of four parts: (1) input, (2) output required, (3) objectives, and (4) Constraints. Table 2 shows the different possibilities for each part of the problem. In the generic resource allocation problem, the input parameters/constants are set by the utility companies or regulatory authorities. In renewable energy sources, number and the selection type of renewable energy sources units primarily depend upon: (1) the geographical area where renewable energy sources need to be deployed [29], (2) the purpose of installation and (3) the expected energy demand. Atmospheric conditions are very important while selecting the appropriate type of renewable

Table 3
Optimization tools.

S. no.	Developer	Softwares/tools	Specifications	Use/application
1	National Renewable Energy Laboratory	HOMER	HOMER is used to assess different options for both stand alone and grid connected power systems. It is licensed to and maintained by Homer Energy. http://www.homerenergy.com	HOMER is used to evaluate different design options for off grid connected and stand alone power generation based on different renewable energy sources
2	National Renewable Energy Laboratory	REFlex	This model is used to evaluate renewable generation as a function of system flexibility and demand response. http://www.nrel.gov/analysis/models_tools.html	REFlex is used to evaluate the generation of renewable energy as a function of the flexibility of the system
3	National Renewable Energy Laboratory	Job and Economic Development Impact (JEDI) Model.	Different JEDI models are available for different renewable energy sources namely, biofuels model, coal model, geothermal model, photovoltaic model and wind model. http://www.nrel.gov/analysis/jedi/	JEDI model is used to evaluate the financial impact of distributed and centralized deployment and operation of a renewable system
4	National Renewable Energy Laboratory	Cost of Renewable Energy Spreadsheet Tool (CREST)	It is spread sheet based software tool which can be used to estimate the cost of the energy and to get insight about economic drivers and the renewable energy sources projects. https://financere.nrel.gov/finance/content/crest-cost-energy-models	CREST can be applied for different renewable energy sources namely, solar, wind, geothermal and fuel cell
5	National Renewable Energy Laboratory	In My Backyard (IMBY): for photovoltaic (PV) Arrays or Small Wind Turbines	IMBY uses a map-based interface to allow to choose the exact location of PV array or wind turbine. Based on the particular location, system size, and other variables, IMBY estimates the electricity production which can be expected from the system. http://www.nrel.gov/eis/imby/about.html	It estimates the electricity, which can be produced with a solar PV array or wind turbine at any location. It can provide quick estimates of renewable energy production at location
6	LINDO Systems	LINGO	It can be used to model and solve Linear, Nonlinear (convex & nonconvex/Global), Quadratic, Quadratically Constrained, Second Order Cone, Stochastic, and Integer optimization models faster, easier and more efficient way. http://www.lindo.com/index.php?option=com_content&view=article&id=2&Itemid=10	Can be applied to optimize any renewable energy system in any scenario or for any objective function
7	Esri	ArcMap 9.3.1	ArcMap is used to view, edit, create and analyze the geospatial data for assessing the potential of different renewable energy sources. http://www.esri.com/software/arcgis/eval-help/arcgis-931	Can be used to find the potential of renewable energy sources in any geographical location
8	RETScreen International	Solar Air Heating Project Model Software	Can be used world-wide to easily evaluate the energy production (or savings), life-cycle costs and greenhouse gas emissions reduction for air heating. http://www.retscreen.net/ang/g_solara.php	The model is designed particularly for the analysis of transpired-plate solar collectors. This technique has been used in numerous applications from small domestic to larger commercial/industrial scale ventilation systems, as well in the air drying processes for various crops
9	RETScreen International	Photovoltaic Project Model Software	Can be used to evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for three basic PV applications: on-grid, off-grid, and water pumping. http://www.retscreen.net/ang/g_photo.php	For on-grid applications the model can be used to evaluate both central-grid and isolated-grid PV systems. For off-grid applications the model can be used to evaluate both stand-alone (PV-battery) and hybrid (PV-battery-genset) systems. For water pumping applications the model can be used to evaluate PV-pump systems
10	RETScreen International	Solar Water Heating Project Model Software.	Can be used to evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction http://www.retscreen.net/ang/g_solarw.php	Can be used for three basic applications namely, domestic hot water, industrial process heat and swimming pools
11	RETScreen International	RETScreen International Wind Energy Project Model Software.	Can be used to evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for different wind energy projects. http://www.retscreen.net/ang/g_win.php	Can be used for central grid connected, micro grid connected and stand alone wind energy projects, ranging in size from large scale multi-turbine wind farms to small scale single-turbine and wind-diesel hybrid systems

energy sources in a particular area [30–33]. Renewable energy sources are mainly deployed in grid-connected mode or stand alone mode. So the mode of operation largely influences the selection and type of renewable energy sources generating units. To optimize the net present value of the project, the lifetime of the renewable energy sources is very important. Optimization algorithms focus on minimizing the total cost and giving significant weight to the operational life of the renewable energy sources generating units. Efficiency of renewable energy sources' units is another factor that plays a significant role in deciding the number and type of renewable energy sources units while optimizing the cost and power production. Renewable energy sources' units requiring less operation and maintenance cost are the choice of the utility companies, which facilitate them to earn more profit. Given the constraints of specific meteorological conditions and geographical locations, some renewable energy sources may be suitable and others may not be appropriate for the specific conditions [34]. Nature of optimization problem will change according to the specific input parameters, required objective function to optimize and the constraints posed by varying realistic conditions (Table 3).

4. Conflicting objectives in renewable energy sources

Historically energy planning was solely targeted towards minimization of cost; but with the evolving socio-economic conditions, there are many other objectives that are considered while making the decision [35]. When more than one objectives are considered simultaneously, they may conflict with one another, e.g., minimization of pollutant material/gases in the environment conflicts with the objectives of minimization of operating cost, minimization of investment and minimization of fuel cost [36,37].

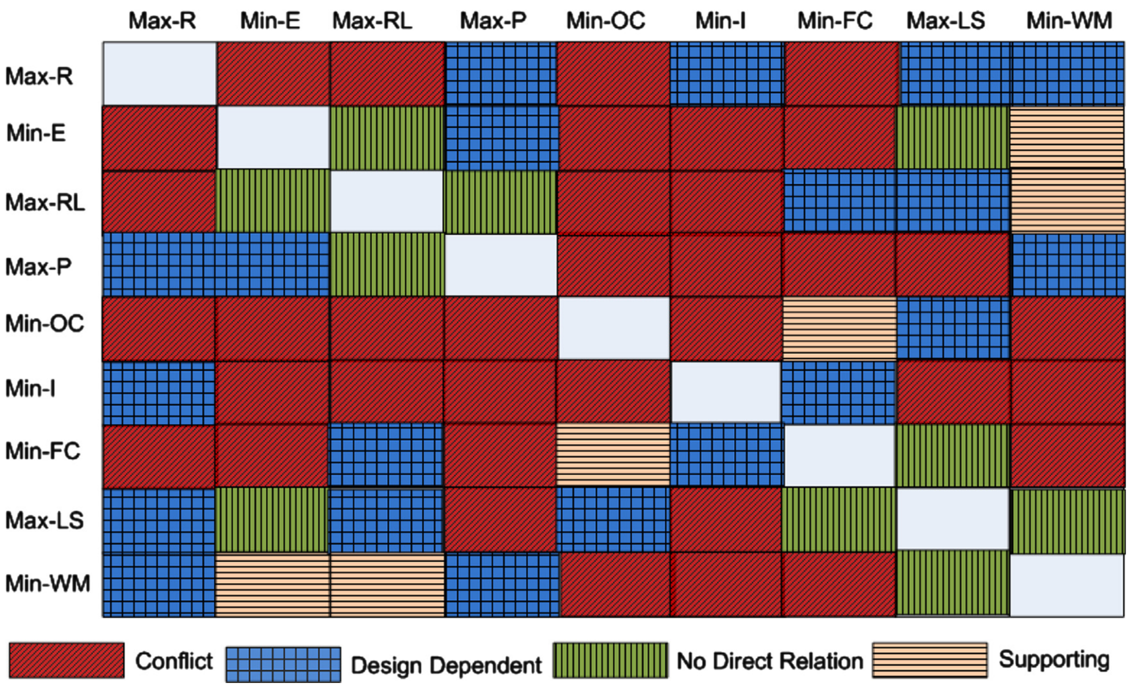

Fig. 5. Relation between conflicting objectives. Max-R: maximize revenue, Min-E: minimize emissions, Max-RL: maximize reliability, Max-P: maximize production, Min-OC: minimize operating cost, Min-I: minimize investment, Min-FC: minimize fuel cost, Max-LS: maximize life span, Min-WM: minimize waste. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

In Fig. 5, different conflicting objectives are shown where, Max-R represents maximization of revenue, Min-E represents minimization of emission, Max-RL represents maximization of reliability, Max-P represents maximization of production, Min-OC represents minimization of operating cost, Min-I represents minimization of investment cost, Min-FC represents minimization of fuel cost, Max-LS represents maximization of life span and Min-WM represents minimization of waste material. Different cells are given different colors depending upon their location in the matrix. Red color shows that objectives corresponding to the respective row and column are conflicting with each other, e.g., example maximization of revenue is in conflict with minimization of harmful emission, minimization of operating cost and minimization of fuel cost. Similarly, blue cell with small boxes shows that the corresponding objectives are design dependent, i.e., they may or may not be in conflict depending on the design of the system. For example, minimization of investment may or may not conflict with maximization of revenue and minimization of fuel cost depending upon the design of the renewable system. Green box with vertical lines shows that the corresponding objectives do not have any direct relation with each other, e.g., minimization of harmful emission has no direct relation with the maximization of reliability and life span of the renewable energy system. Light pink box with horizontal lines shows that the corresponding objectives go side by side with each other, e.g., minimization of fuel cost and minimization of operating cost. In the following, we discuss each objective separately and its relation with other objectives. Minimization of harmful emission has been studied in numerous articles, e.g., in [38–41], where the authors have used linear programming and hybrid optimization model to optimize the biofuel based energy generation systems. They consider the conflicting objectives of minimization of pollutant emission and maximization of production and economic efficiency. An optimization model based on geographical information system has been proposed in [42] to identify the locations for biofuel facilities while considering various conflicting objectives namely, emission of waste material, availability of raw material for biofuel, and operational cost. An energy planning model has been presented in [43] by integrating mixed integer and interval parameter linear programming. The authors formulated the optimization model by considering expense of energy supply, expansion in capacity and energy conversion and utilization ratio as decision variables. They presented a case study for the city of Waterloo, Canada, to assist sustainable energy development and reduce harmful emissions.

Chen et al. [44] proposed an energy system planning model to reduce carbon dioxide emission and ensure energy supply safety with a minimum risk of interruption. The authors have proposed an interval-robust non-linear optimization method by integrating interval parameter planning and robust optimization to cope with the random conditions. The used model considered continuous as well as binary decision variables. Continuous variables were used to represent the flow of energy and the incremental improvement in the capacity, and the binary variables were used to depict whether or not any specific technology to be deployed or action to be taken.

In [45], the authors have proposed a mixed integer linear programming model to reduce the cost per unit of power under the constraints of efficiency and carbon emission. In [46] an energy system planning model has been considered for the region of the greater southern Appalachian mountains of the eastern United States. The model formulates an objective function to establish a balance between the annual cost of energy generation and the amount of greenhouse gas emissions. In [47], a modified energy flow optimization model has been proposed, which gives solution for optimal power plants to be deployed with the objective function that minimizes the total cost of production and carbon dioxide emission and maximizes the robustness.

A multi-criteria decision making has been used to develop an optimization model to minimize the harmful emission and estimated costs of production for a hybrid photovoltaic-wind turbine system [48]. In [49], the authors have used a non-linear optimization model to minimize the noise emission and maximize the production by improving the aerodynamic efficiency of the blade of wind turbine. Particle swarm optimization has been used in

[50–52] to optimize the blades of the wind and wave energy turbines with the objectives of minimizing manufacturing cost, reducing noise emission and maximizing power production.

Maximization of revenue conflicts with the objectives of minimization of emission, maximization of reliability, minimization of operating cost and minimization of fuel cost. Many optimization models have been proposed to maximize profit or revenue, e.g., an evolutionary algorithm has been used in [53] to solve mixed-integer type problem. This problem maximizes the profit by finding the optimal structure of wind farm consisting of number of units, their type and height. In [54,55], the authors have proposed an optimization model to maximize the profit from the joint operation of wind farm and pumped hydro storage plant. Objective of maximization of reliability directly conflicts with the objectives of maximization of revenue, minimization of operating cost and minimization of investment.

In [56], the authors have used linear programming to find the appropriate renewable energy sources by considering their technology, availability and reliability. Reliability has been considered as a constraint to minimize the cost and maximize efficiency in the optimization model considered by [45]. In [57], the authors have used genetic algorithm to find the optimal wind farm design with the objective of maximizing reliability and minimizing production cost by using different components of wind farm and their technical specifications as input variable. Reliability of power supply of the wind generation system is affected by the system cost and uncertain weather conditions.

In [58], the authors have proposed an optimization model to maximize the reliability of the wind generation system and minimize the production cost by estimating the appropriate size of the system. In [59,60], the authors have considered a hybrid renewable energy sources consisting of wind turbine and photovoltaic cells. They have calculated the optimal size of the hybrid system to minimize the system cost and maximize the reliability. In [61–64], the authors have proposed an optimization model using iterative techniques to estimate the optimal size of the hybrid stand alone renewable energy sources to ensure the system reliability with minimum cost. In [64], the authors showed that the number of capacity factors of renewable energy sources namely, wind turbines, photovoltaic cells and the storage capacity of batteries increase with increasing reliability levels.

The maximization of power production from the renewable energy sources conflicts with the objectives of minimization of operating cost, fuel cost and investment. This also conflicts with the objective of maximization of life span. In [65], a polynomial optimization scheme has been proposed to increase the total production of electricity from renewable as well as from conventional sources. Analytical optimization techniques have been reviewed in [66] to optimize the production from combined heat and power systems. An optimization model using combined heuristic and nonlinear mathematical programming techniques has been proposed in [67] to maximize the electric power production from offshore wind farms.

In [68], the authors have used momentum theory and evolutionary algorithm to optimize the vertical axis wind turbine with the objective of maximizing electricity production over a definite period. A hybrid microgrid/stand alone energy system design has been considered in [69]. The authors have used particle swarm optimization technique to find the optimal balance between the cost and the energy production. In [70], a water supply system has been exploited to generate electricity by replacing pressure reducing valves with water turbines [71]. Linear programming approach has been used to maximize the production of electricity. Heuristic algorithm has been used to optimize the design of blade for a wind turbine to achieve highest electricity production over the year and reduce the manufacturing cost [72,73]. A wind farm layout design has been formulated as nonlinear optimization problem to optimize the layout for maximum energy production in [74].

The objective of minimizing the operating cost conflicts with the objectives of maximizing the revenue, minimizing the emission, maximizing the reliability, maximizing the production, minimizing the investment, and minimizing the waste material. Various multi-objective optimization models are available in the literature to find optimal balance between the minimization of operating cost and other conflicting objectives. Ref. [75] reviews different particle swarm optimization techniques focused to minimize the operating cost. In [76], the authors have proposed a fuzzy self-adaptive particle swarm optimization algorithm to plan electricity production in a stand alone hybrid renewable energy sources considering operating cost and harmful emission as two conflicting objectives to be minimized. Size optimization of different hybrid renewable energy system has been reviewed in [77] using different optimization techniques, namely genetic algorithm, particle swarm optimization, simulated annealing, ant colony algorithm and artificial immune system algorithm. These optimization techniques have been used for a mix of combinations of different hybrid renewable energy sources with the objective of minimizing investment and operating cost.

Minimization of investment conflicts with many other objectives of renewable energy sources is shown in Fig. 5. In [65], authors have used polynomial optimization scheme to find the optimal balance between the operating cost and the investment cost. An optimization model has been formulated in [46] considering an optimal mix of renewable energy sources and conventional fossil fuel based energy systems to find the optimal balance between multiple objectives, namely operating cost, greenhouse gas emissions and investment cost. In [78], an optimization model is presented to forecast total energy generation from three sources namely, wind, solar and biomass. The model maximizes total electricity generation from these resources while considering various constraints including the investment cost. Ref. [79] presents the review of different optimization techniques for the layout design of small hydro power plants. The review is focused on minimizing the installation cost under given constraints. In [53], an evolutive algorithm has been used to optimize the wind farm design with the objective of minimization of investment cost and maximization of the revenue. In [80] combinatorial optimization has been used to find the wind farm design with the objective function of minimizing the investment cost while maximization of the production of electricity.

The objective of minimizing the fuel cost conflicts with various other objectives as shown in Fig. 5. Various optimization techniques have been used to tackle the objective of fuel cost minimization along with other conflicting objectives, e.g., Elysia et al. [81] proposed a constrained optimization model for a hybrid solar–fossil fuel unit to maximize the power production against the fixed cost of fuel. An optimization model has been proposed in [82] to minimize the fuel cost and transmission losses for a hybrid power generation system consisting of conventional power plants and those of based on renewable energy sources.

Maximization of life span conflicts with the objectives of maximization of production and minimization of investment. A mixed integer optimization model has been formulated in [83] to design a distributed hybrid renewable energy generation system with the objective of maximization of life span and minimization of transmission cost. In [84], the authors have proposed an optimization framework for producing sustainable substitutes to chemical process with the objective of minimization of waste materials. They used different simulators to implement this multi-objective optimization framework. In [85], the authors have proposed a model for the design of a stand alone hybrid system

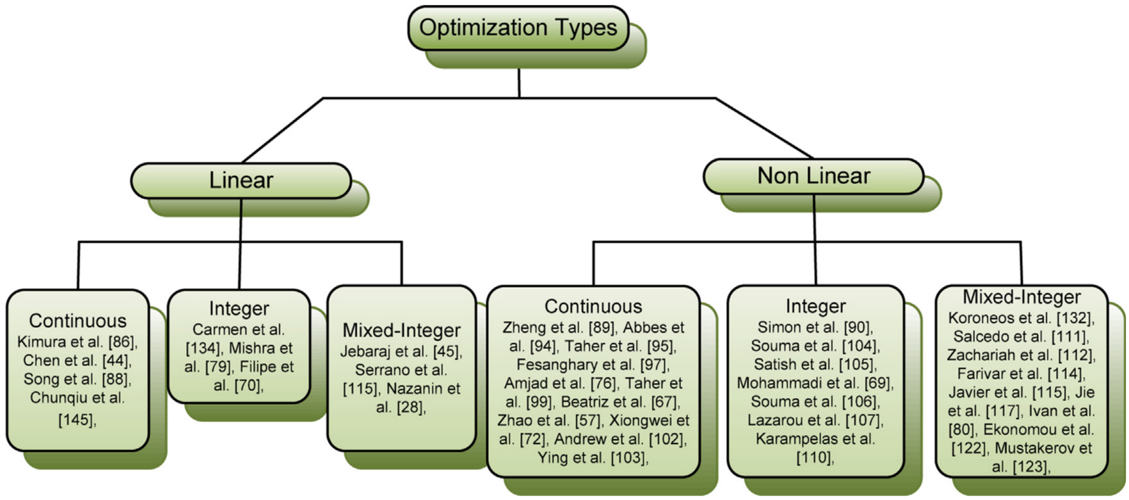

Fig. 6. Optimization types.

to minimize the initial investment, life cycle cost and pollutant emission.

5. Types of optimization used in renewable energy sources

Design, planning and control problems in renewable energy sources have been formulated differently depending upon the particular renewable energy sources, objective function and the environment of operation. Fig. 6 shows the classification of optimization in two broad categories, namely linear and non-linear optimization techniques which are discussed in detail below.

5.1. Linear optimization techniques

In [86], the authors have formulated the linear optimization problem for large capacity hybrid power systems by employing recurrent neural networks. They optimized the grid connected system comprising of wind and solar energy for the objective function of minimization of the electric power from the power grid.

There is a lot of published literature available on the layout optimization of the wind farms. For example, in [87], the layout problem has been optimized by finding the optimal height of the wind turbine tower. The height of the tower was optimized based on the speed of the wind at the particular site, the power characteristics of the turbine, wake effect model and the cost model. The authors in [87] argued that the tower with higher heights does not always produce optimal results; instead there is an optimal height of the tower that can give better results. In [88], the authors have used bionic method to optimize the layout of the wind turbines and compared the results with that of the genetic algorithm. They showed that the results with the proposed method were better as compared to the earlier methods specially with the irregular geographical area. In [89,90], the layout problem of wind turbines in the farm has been tackled by using bio-inspired optimization techniques. In [45], the authors have formulated a mixed-integer linear optimization problem to satisfy the demand of electricity with minimum expenses. They built a multi-criteria decision making system that enables the investors and government agencies to make proper investments in the renewable energy sources. In [53], the authors formulated a mixed-integer linear programming model and used an evolutive algorithm to optimize the wind farm design with the objective of minimization of investment cost and maximization of the profit. In [91], Hugo et al. proposed a mixed integer linear optimization to optimize the operation of the hybrid renewable energy sources. They applied the proposed method of optimized scheduling for different renewable energy sources' units in Budapest University of Technology and Economics. A mixed integer linear optimization model has been proposed in [92] for optimized layout of wind turbines in a farm. The authors in [92] stated that contrary to the earlier work, their method was more robust to handle the uncertainties in the wind direction. In [93], an optimization method has been proposed to optimize the profitability and limit the environmental deteriorations. The authors proposed a mixed integer mathematical programming approach to optimize the supply of ethanol in northern Italy.

5.2. Nonlinear optimization techniques

In [94], the authors have proposed a continuous non-linear optimization method to minimize the loss of power supply probability of hybrid stand alone renewable energy sources consisting of wind, photovoltaic and batteries. Different models have been formulated to ensure the satisfaction of electricity demand through optimal operation of different renewable energy sources' units [95–98].

A fuzzy self-adaptive particle swarm optimization technique has been used to optimize the cost of operation for grid connected hybrid renewable energy sources in [76,99,100]. A combined heuristic and non-linear optimization method has been proposed in [67]. The optimization model is focused to maximize the potential power generation of the offshore wind farm by deploying the wind turbines appropriately. The model also tackled the problem of wake effect which could result in improving the operational life of the turbines.

Wind farm layout problem has been formulated as non-linear optimization model in [57]. The authors in this reference have used genetic algorithm to optimally place the wind turbines with the objective of maximizing reliability and minimizing production cost. In [101], the authors have presented an optimal polygonal approximation algorithm to find the optimal micro-siting of turbines in the wind farm. An optimal blade design method has been proposed in [72] by using heuristic algorithm to maximize the annual electricity generation and minimize the manufacturing cost. Data mining and evolutionary computation have been used in [102] to solve the non-linear optimization problem of blade pitch and yaw angle of the wind turbine with the objective of maximization of power generation. Non-linear optimization of hub

height of the wind turbine has been proposed in [103] by using a nested genetic algorithm. The author argued that the optimal hub height can result in more power generation by using the same number of wind turbines.

A combined optimization model for the layout and selection of turbines has been proposed in [104]. The authors used mixed discrete particle swarm optimization algorithm to optimize the selection and deployment of the wind turbines. The model was implemented to design a wind farm in North Dakota. They observed the increase in capacity factor by an amount of 6.4%. In [105], authors have used non-linear optimization to optimize the size of distributed generation units and their optimal placement. They used particle swarm optimization algorithm to optimize the problem with the objective of minimization of the real power loss and improving the voltage profile. An integer non-linear optimization model has been proposed in [69] to optimize the hybrid renewable energy sources connected with the central distribution system. The authors in this reference proposed the model with the objective of minimization of the cost of energy production and minimization of the power consumed from the main grid.

In [106], a constrained particle swarm optimization algorithm has been used to optimize non-linear problem of the wind farm layout with the objective of maximization of the total power generation under constraints of farm size and minimum distance between the turbines. A non-linear integer optimization model has been used to optimize the wind farm layout design [107–109]. The objective function of the proposed model is minimization of the cost of electricity production by deploying the optimal number of wind turbine and using optimal area of the land. The wind farm layout problem has been tackled in [110] by using non-linear integer optimization. In this reference, the cost of energy production is reduced by using less number of wind turbines over the minimum area of the land. The authors compared the performance of their method with those of earlier methods and argued that the performance of their proposed method was better than the others.

A multi-objective mixed integer nonlinear optimization model has been used to optimize the performance of the solar collectors with the objective of maximization of the profit and minimization of the environmental pollution [111]. A mixed integer non-linear optimization has been used to optimize the hybrid renewable energy sources with the objective of minimization of the levelized cost of electricity and the power supply [112]. A review of optimal planning for distributed generation by using different renewable energy sources has been presented in [113]. In [114], a multi-objective optimization was used to find the appropriate size and site of the distributed generation units to improve the power supply and quality. Mixed integer non-linear optimization has been used in [115,116] to find the optimal location for the wind turbine to reduce the cost of electricity produced. The authors in [115] implemented the model under various realistic constraints. In [117], the authors have formulated a planning methodology for the wind farms by making use of newly proposed cost and power generation models. The model provided information relating to the deployment cost of the wind farm, cost of operation and maintenance per annum, and the total cost. In [118–121], condition based and opportunistic optimization techniques have been used to minimize the maintenance cost.

Combinatorial optimization has been used in [80,122,123] to model the wind park design with the objective of minimization of investment and maximization of total electricity generation from the wind park. A mixed integer nonlinear optimization is proposed in [124] to deal with the short term scheduling issues in hydro power systems considering various realistic constraints. A wind power system integrated with compressed air energy storage has been modeled as mixed integer non-linear optimization in [125]. The model has been formulated for optimization with objective function of maximization of profit and minimization of operating cost.

6. Optimization techniques applied to renewable energy sources planned for different end users

To cope with the inherent intermittent nature of the renewable energy sources, various combinations of renewable energy sources can be used in different geographical locations and countries. These various combinations of renewable energy sources for different end users are being formulated by using different optimization techniques suitable for different scenarios as shown

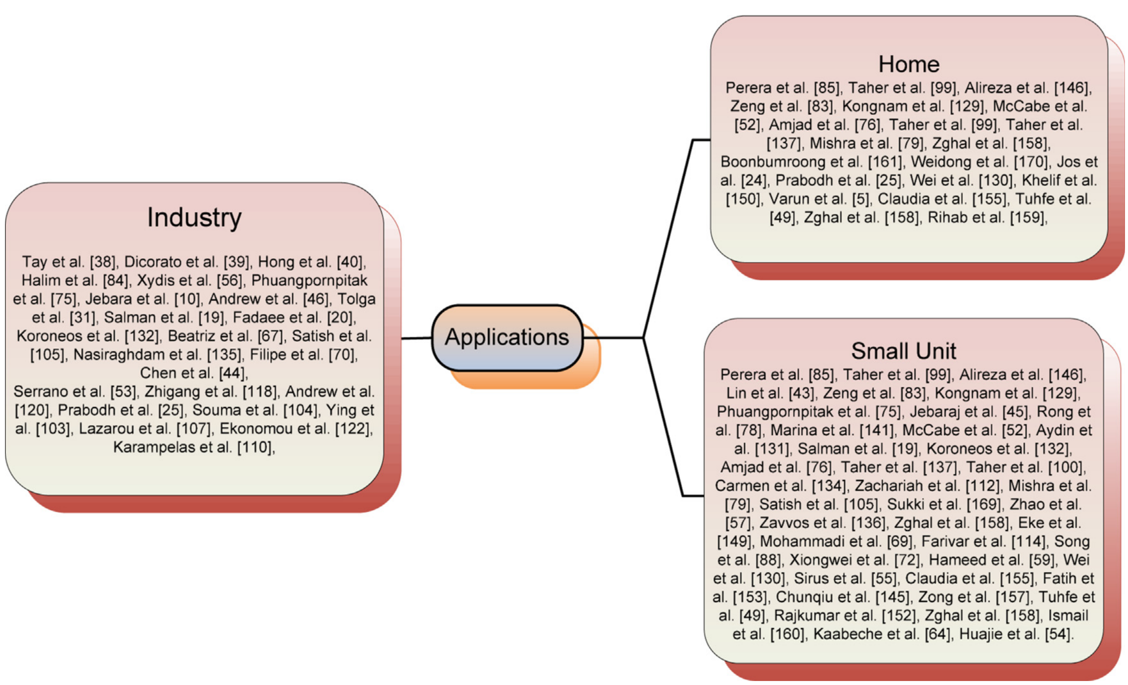

Fig. 7. Application areas.

in Fig. 7. In this section, a review of the optimization techniques applied for optimizing the electricity generation using renewable energy sources is presented. These techniques can be applied to industry, small units and home.

6.1. Optimization techniques applied to renewable energy sources for industry and central grid

Governments, utility companies and the other stakeholders have realized the importance of renewable energy sources to reduce the dependency on fossil fuels for the generation of electricity and hence reduce carbon dioxide emission [1]. Optimization techniques are being applied for the generation process as well as for the consumption of renewable energy sources based electricity. A hybrid optimization technique has been used in [38] to optimize the environmental and economic efficiency of a biorefinery. In [126], the authors have reviewed various multi-criteria decision making techniques to optimize the bioenergy systems while considering various objectives including environmental and economic objectives. In [127], the authors have used evolutionary algorithm to optimize the system while considering optimal power flow and emission problem simultaneously. They argued that the proposed model provides economically as well as environmentally viable solution. A simulated annealing algorithm has been used in [84] to optimize the biodiesel production plant by using multi-objective optimization technique with the objective of minimization of waste material and energy and maximization of profit/revenue. An optimization framework has been proposed in [56] to meet the energy demands of Greece. The proposed model has used multi-objective optimization for energy system planning by deploying energy recovery units from the solid waste of municipality. A fuzzy-based linear programming model has been proposed in [45] to optimize the allocation of renewable energy sources for centralized and distributed generation in India. The authors stated that the implementation of their proposed model could result in more appropriate electricity distribution. A decision support system based on multi-objective linear programming model has been proposed in [46] for energy planning, which could facilitate the integration of conventional energy sources and renewable energy sources. The objective of the proposed model was to optimally constitute the energy system comprising of renewable energy sources and fossil fuel based generation. In [78], an optimization model for hybrid renewable energy sources based electricity generation and its application in China has been proposed.The model uses past data and future forecast to predict the renewable energy sources potential in China. A multi-criteria decision support system has been proposed in [128] for the evaluation and selection of different renewable energy sources to enable the decision makers reach a clear decision.

Wind energy is abundantly available, but it is intermittent; hence, wind turbines operation needs to be properly controlled. In [129], control problem of wind turbine has been optimized using particle swarm optimization algorithm with the objective of maximization of the output power. Hybrid grid connected renewable energy sources are more reliable as compared to stand alone renewable energy sources [25,130]. In [131], an optimization model using multi-criteria decision making techniques has been proposed for the site selection of hybrid wind–solar renewable energy sources. The model considers environmental and economic objectives simultaneously along with other realistic constraints. An iterative heuristic algorithm has been used in [19] to solve the NP-hard problem of wind farm layout optimization with the objective of minimization of cost and maximization of energy generation. A multi-objective optimization model has been proposed in [132] to find the optimal combination of hybrid renewable energy sources to minimize the total cost of electricity generation while reducing the carbon dioxide emission. A heuristic method has been used in [67,133] to solve nonlinear optimization of wind farm layout and positioning problem for maximization of power production and minimization of the wake effect losses. Optimal selection of hybrid solar–wind park is discussed in [134] by using integer linear programming model. The authors considered various factors namely, production, distance from the main grid, cost and environmental factors while selecting the optimal location.

Particle swarm optimization technique has been used in [105] for optimizing the placement of distributed generation units so as to minimize the real power losses. A multi-objective optimization has been proposed in [135] to optimize the size of hydro power plant. The authors considered the cost of generation, power loss and pollution emission while finding the optimal size of the hybrid generating units. Optimization of electrical system consisting of offshore wind farms has been proposed in [57] using genetic algorithm. The proposed model optimized the system with respect to production cost and the reliability of power supply. An optimization model using finite element analysis has been proposed in [136] to optimize the mass of the generators to be used with offshore wind turbines. Optimization of the operational planning for wind and hydro power plant based hybrid power supply system has been proposed in [70]. The authors used linear programming to optimize the planning with the objective of maximization of energy production and minimization of energy consumption.

6.2. Optimization techniques applied to renewable energy sources for small units

To satisfy the needs of small isolated units or localities, renewable energy sources based distributed electricity generation has been proposed in [137,138]. To cater for energy requirements of isolated localities, either stand alone or grid connected systems are being used. The connection with the grid is to ensure the reliability of power supply during the time renewable energy sources systems are unable to satisfy the demand of local consumers and to sell the extra power to the utility company in case the power generated by renewable energy sources is in access of local demand. A stand alone energy system consisting of renewable energy sources is proposed in [139] by integrating multi-objective optimization and multi-criteria decision making techniques. The authors proposed a solution while considering several conflicting objectives simultaneously. A regional energy and greenhouse gas (GHG) planning model has been proposed in [140] to enable the decision makers to consider multiple objectives while designing the system.

In [43], the authors have integrated the mixed-integer and interval parameter linear programming techniques to develop an energy planning model for a small community. They optimized the system for the objective of cost minimization considering the economic, environmental and demand constraints. A multi-agent solution has been presented in [83] for the management of distributed hybrid renewable energy sources. An optimization model based on multi-criteria decision method for analysis of energy demands of a specific area has been proposed in [141] to measure the reliability of the energy systems under different demand and contexts. In [76], a multi-operation management has been proposed by using fuzzy self-adaptive particle swarm optimization algorithm for a hybrid renewable energy sources system feeding a locality. The proposed renewable energy sources system formed the micro grid having connectivity with the main utility grid to further strengthen the reliability of power supply.

A probabilistic cost and production optimization model has been proposed in [99,100] for the operation management of the

hybrid micro-grid renewable energy sources connected with main grid. A stand alone, hybrid solar-wind system having energy storage capability in the form of hydrogen is proposed in [112,142]. The optimal size of the system was found with the objective of no loss of power supply and minimum levelized cost of energy using search algorithm.

Small hydropower systems are the best way for achieving the sustainable energy. In [79], the authors have reviewed different optimization techniques, which have been proposed for the optimal installation of small hydropower plants. A techno-economical optimization method has been proposed in [58,143,144] for sizing of a stand alone wind farm with the objective function of satisfying the energy requirements. In [145], the authors have used Gaussian particle swarm optimization technique to find the optimized layout of the wind farm with the objective of maximization of the electrical power output. A hybrid possibilistic–probabilistic evaluation tool has been proposed in [146] to analyze the effect of uncertainties on distribution network and find the optimal size of the wind turbine. Geometrical optimization has been used in [49] to optimize the design of the airfoil for small wind turbine. The optimization objective was to reduce the noise emission and maximize the power output. Multi-objective optimization has been used in [147,148] to optimize the airfoil shape of different turbines. Optimization of a hybrid wind/photovoltaic system is proposed in [149] with the objective of finding optimal combination of solar/wind generating units to meet the energy requirements of the solar energy institute of Ege University in Izmir, Turkey. An optimal design of hybrid solar–wind renewable energy sources based micro-grid has been proposed in [69] using particle swarm optimization algorithm with the objective of minimization of overall cost of the system.

Widespread use of hybrid electric vehicles is triggering the requirement of charging stations powered by renewable energy sources [150]. In [114,151], an optimal sizing and siting for deployment of distributed generation system is presented using genetic algorithm. Open space particle swarm optimization technique has been used in [59] to optimize the size of hybrid solar–wind renewable energy sources with the objective to minimize the total system cost and loss of power supply probability. A techno-economical optimization using adaptive neuro fuzzy interface technique has been used in [152] to optimize a hybrid renewable energy sources system for minimizing the loss of power supply probability. Optimal operation management system for hybrid micro-grid connected renewable energy sources has been proposed in [55] using adaptive modified firely algorithm to cope with different uncertainties associated with different renewable energy sources. Contrary to traditional deterministic techniques to forecast the solar energy potential, stochastic techniques [153,154] more accurately model the solar radiations. In [155,156], the authors analyzed different parameters affecting the size of stand alone solar systems and developed a stochastic model for optimal sizing of the system. They compared the performance of their proposed stochastic method with deterministic method and concluded that their proposed method performed better.

A combinatorial optimization technique has been used in [157] to find optimal size of the hybrid photovoltaic-wind energy system by using branch and bound algorithm. Iterative technique has been used in [64] to optimize the capacity sizes of different components of hybrid photovoltaic/wind power generation system using battery bank. A review and comparison of different optimization techniques applied to hybrid renewable energy sources has been presented in [24]. A techno-economical optimization using mathematical modeling technique has been used in [158,159] to optimize a stand alone solar system to minimize the loss of power supply probability. Genetic algorithm has been used in [160] to analyze and find the optimal hybrid system consisting of photovoltaic panels, a battery bank and a diesel generator. A stand alone hybrid system consisting of PV, wind and diesel was optimized using genetic algorithm in [161] for the objective function of cost minimization by prolonging the working life of the system.

6.3. Optimization techniques applied to renewable energy sources for home users

The use of renewable energy sources is not limited to the generation of electricity, rather there are many other applications where renewable energy can be used, e.g., renewable energy sources is being used for domestic heating applications. Different optimization techniques have been used to optimize the use of renewable energy sources in various types of domestic heating applications, e.g., [162] compares different optimization criteria for the domestic hot water system based on solar energy. A genetic algorithm has been used in [163] to optimize the solar heating system. The authors also proposed an optimization technique based on Hook–Jeeves algorithm to minimize the life cycle cost. A technique has been proposed in [164] to find the design space for synthesis, analysis, and optimization of solar water heating system. Mono- and multi-objective genetic algorithms have been used in [165] to find the optimal parameters of the solar based domestic hot water system. The authors argued that the inclusion of phase change materials in the thermal energy storage system is not beneficial for the performance of the hot water system. Modeling and optimization of solar energy based heat pump using ice slurry has been proposed in [166] to minimize the energy required for heating and hot water system. A particle swarm optimization technique has been used in [167] to optimize the performance of the flat plate solar air heater. An analytical model has been proposed to predict the performance of a parabolic dish solar concentrator in [168–170] to maximize the collection of thermal energy over the year.

To cope with the intermittency associated with the renewable energy sources, different energy storage systems are used. In [171], optimization of a hybrid energy storage system consisting of conventional lead acid batteries and ultra capacitors has been proposed. Thermoelectric modules are used to keep the temperature of the photovoltaic modules within the allowable limits. A genetic algorithm has been proposed in [172]. The algorithm finds the optimal amount of electrical current for the thermoelectric cooling module to create maximum generated power by the photovoltaic system. A hybrid optimization model consisting of particle swarm and Hook–Jeeves has been used to optimize the solar heating system in [173]. The proposed optimization algorithm is focused on minimizing the life cycle cost of the system. An active demand side management has been presented and optimized in [174] for a house having photovoltaic cell based energy system connected with the grid. The proposed method is used to minimize the energy consumption from the grid and loss of energy. Investigation of the economic, technical and environmental performance of residential photovoltaic system has been presented in [175]. The proposed method has been used to find the optimal size and number of the photovoltaic panels to minimize the life cycle cost.

7. Conclusion and future directions

In this paper, we presented a detailed review of different optimization methods for deployment and operation of renewable energy sources (renewable energy sources) based generating units. We summarized existing research literature published in this area. We reviewed and categorized this area with respect to

different types of renewable energy sources, different modes of operation, types of objective functions for optimization and different geographical areas from which research publication are emanating. We presented a general resource allocation problem by dividing it into four parts, i.e., input, output, objectives and constraints, and specified different possibilities for each part. We reviewed different objective used in defining the optimization problems, i.e., maximization of revenue, minimization of emission, maximization of reliability, maximization of production, minimization of operating cost, minimization of investment cost, minimization of fuel cost, maximization of life span and minimization of waste material. We further showed the relation of each objective function with other objective functions. We also presented different types of linear and non-linear optimization algorithms used in renewable energy sources. We review optimization techniques for applications with respect to different end users that we divide into 3 categories: industry, small units and home. We showed that there is an ever increasing research activity in the area of optimization methods for renewable energy sources, with this increase expected to concentrate in future on renewable energy sources such as hydro, geothermal, biomass and biofuel, and grid connected renewable energy sources.

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